Journal of Template

Vol. 00, No. 0, 0000

Laser Forming of Thin Film Metallic Glass*

Masaaki OTSU**, Yuki IDE**, Junpei SAKURAI***,
Seiichi HATA*** and Kazuki TAKASHIMA**

**Department of Materials Science and Engineering, Kumamoto University,
2-39-1, Kurokami, Kumamoto, 860-8555, Japan
E-mail: otsu@msre.kumamoto-u.ac.jp
***Precision and Intelligence Laboratory, Tokyo Institute of Technology,
4259, Nagatsuta-Cho, Midori-Ku, Yokohama, Kanagawa, 226-8503, Japan

Abstract

Palladium based thin film metallic glasses were plastically bent by laser forming process. Thin films of $Pd_{77}Cu_6Si_{17}$ with a thickness of 0.028mm and $Pd_{40}Ni_{40}P_{20}$ with a thickness of 0.017mm were used for specimen. A 50W YAG laser was employed for forming. Variation of bending angle was investigated by changing working conditions such as laser power, laser operation mode (continuous wave and Q-switch pulsed modes), Q-sw frequency, scanning velocity and scanning number. From the experimental results, both thin films of $Pd_{77}Cu_6Si_{17}$ and $Pd_{40}Ni_{40}P_{20}$ were successfully bent for more than 85º. The formed thin films did not crystallize but were amorphous. As scanning number increased, bending angle also increased but increasing rate decreased. When laser power and scanning velocity were changed, bending angle had a peak. When Q-sw frequency was changed, bending angle had a broad peak in $Pd_{77}Cu_6Si_{17}$ case, but that was larger as frequency was smaller in $Pd_{40}Ni_{40}P_{20}$ case.

Key words: Micro Forming, Laser Forming, Bending, Metallic Glass, Thin Film, MEMS

1. Introduction

Electric devices and semiconductor devices having lighter weight and higher performance are required for appliances and automotive sensors and actuators. MEMS (Micro Electro Mechanical Systems) devices are promising, and to enhance reducing the device size and weight, and improving performance, it is necessary to fabricate them with not only two-dimensional but also three-dimensional structure in micrometer order. However, since conventional fabrication methods for microdevices are layer integration process like lithography, it is difficult to manufacture three-dimensional structure with large height. Therefore new forming methods are required for making microdevices having three-dimensional structure with large height, and plastic working methods, especially bending of thin films, are very efficient ones.

Those microdevices are ordinarily consisted of silicon or silicon compounds because those materials are suitable for micro-manufacturing process such as lithography, LIGA process and so on. Those materials, however, have crystalline structure, and mechanical and physical properties depend on crystallographic orientation and it is hard to control the distribution of crystallographic orientation in devices to utilize or eliminate anisotropy of the properties. To eliminate dependency of crystallographic orientation on mechanical and physical properties of microdevice material, amorphous materials especially metallic glasses are tried to apply to microdevices. However, metallic glasses are brittle and difficult

*Received XX Xxx, 200X (No. XX-XXXX)
[DOI: 00.0000/ABCDE.2006.000000]

Vol. 00, No. 0, 0000

to deform plastically at room temperature.

Recently, laser forming process is remarkable for forming sheet and foil materials without forming punches and dies. By this method, materials are plastically deformed with thermal stress induced by rapid heating due to laser irradiation. Laser forming process forms sheets with compression at laser irradiated area while conventional process forms with mechanical stretching. Thus, this process may be useful for forming brittle materials that is easy to fracture by tensile stress and very strong against compressive stress. There are a lot of reports about forming sheets of carbon steel, stainless steel [(1)], aluminum alloy [(2), (3)], titanium alloy [(4)] and plastics, these are all ductile material, however, a few researches are performed about forming brittle materials, silicon and glass, by laser forming process [(5), (6)]. If laser beam is irradiated to thin film metallic glasses, it is considerable that those materials are heated up and become ductile and easy to form plastically.

In the present study, the effect of laser forming conditions such as laser power, scanning velocity, Q-sw frequency, and scanning number on bending angle of palladium based metallic glasses thin films was investigated.

Nomenclature

N : scanning number
P : laser power, W
f : Q-switch frequency, kHz
v : laser scanning velocity, mm/s
ϕ : diffraction angle, ^{o}
θ : bending angle, ^{o}

2. Experimental Method

In the present study, two kinds of thin film palladium based metallic glasses as shown in Table 1 [(7), (8)] were used for specimens.

An experimental apparatus for laser forming and shape measurement is shown in Fig. 1. A 50W YAG laser was used for laser forming. Specimen was fixed to an NC table at only an end like cantilever. For forming, laser beam was irradiated on the specimen and scanned by galvano mirrors to perpendicular to the longitudinal direction. After forming, the specimen

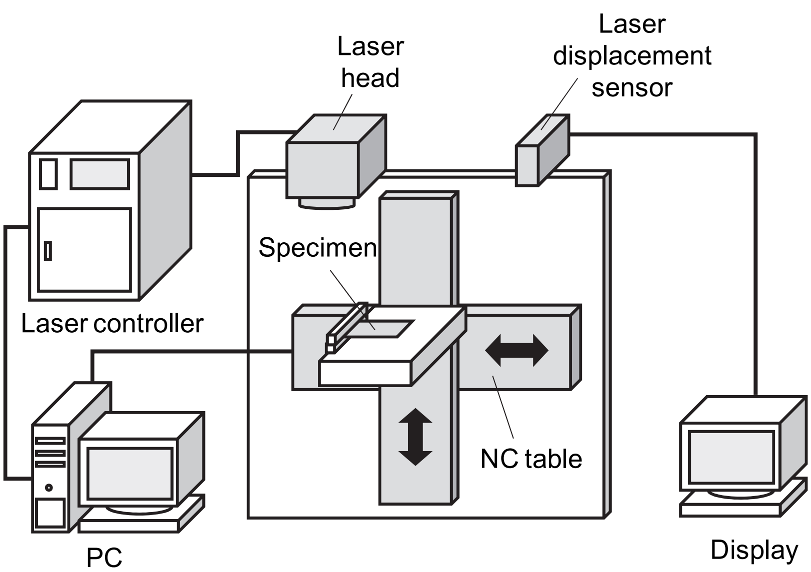


Fig. 1 Experimental apparatus for laser forming of thin film metallic glass

was moved to shape measuring place and bending angle was measured by a line scan type laser displacement sensor.

Working conditions are shown in Table 2. Laser power, scanning velocity, scanning number and Q-sw frequency were changed and bending angle was investigated. Although operation mode of laser device was used both CW and Q-switch pulsed modes, results at only Q-switch pulsed mode are shown in this paper because specimens were melted and fractured at CW mode.

Table 1 Material and size of specimens

Material	$Pd_{77}Cu_6Si_{17}$	$Pd_{40}Ni_{40}P_{20}$
Glass transition temperature [K]	657	578
Crystallization temperature [K]	680	651
Length [mm]	10	10
Width [mm]	1.45	1.45
Thickness [mm]	0.028	0.017

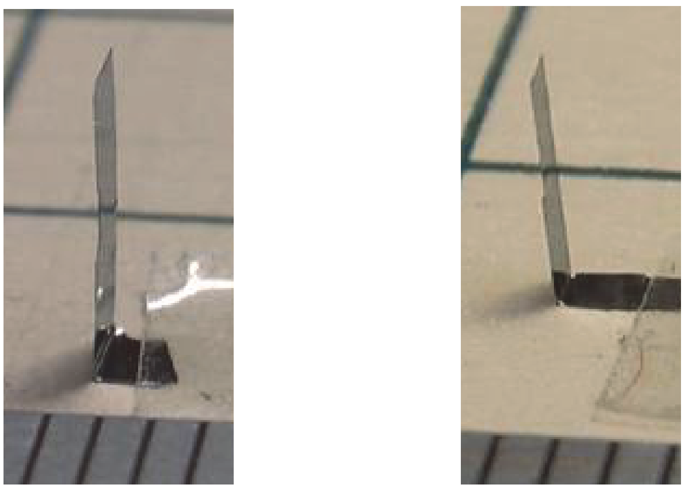
Table 2 Laser forming conditions

Operation mode	Q-sw Pulsed / CW
Wave length [nm]	1064
Frequency, f [kHz]	2-30, CW
Laser power, P [W]	0.5-7
Scanning velocity, v [mm/s]	15-65
Scanning number, N	1-80
Atmosphere	Air

3. Results and Discussions

3.1 Formed Shape and Microstructure

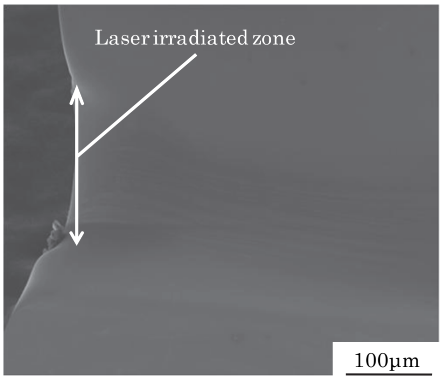
Appearances of formed thin film metallic glasses are shown in Fig. 2. When scanning velocity was v=40mm/s, Q-sw frequency was f=3.0kHz and scanning number was N=80, bending angle of $Pd_{77}Cu_6Si_{17}$ was θ=89.0º at the laser power of P=3.0W and that of $Pd_{40}Ni_{40}P_{20}$ was θ=86.5º at P=1.5W, respectively.



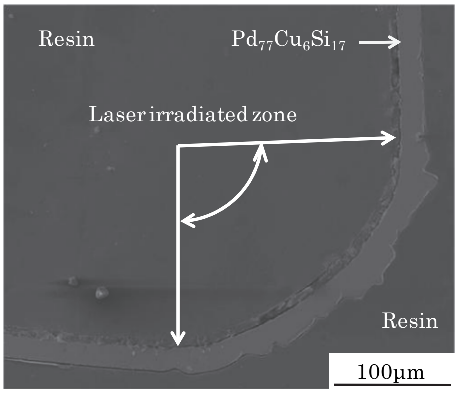
(a) $Pd_{77}Cu_6Si_{17}$ (P=3.0W, θ=89.0º) (b) $Pd_{40}Ni_{40}P_{20}$ (P=1.5W, θ=86.5º)

Fig. 2 Appearance of formed specimens (v=40mm/s, f=3.0kHz, N=80)

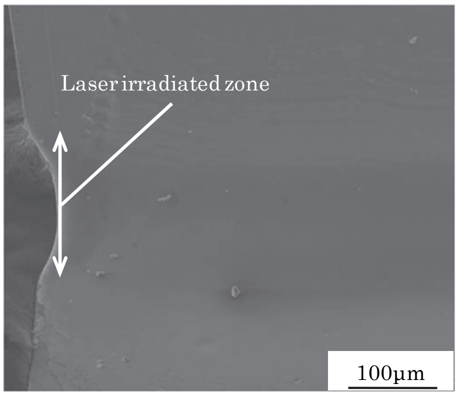
Figure 3 shows SEM images of surface and cross section of formed specimens. Melting



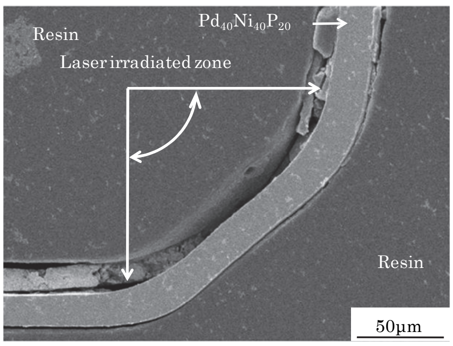
(a) Surface ($Pd_{77}Cu_6Si_{17}$, *P*=3.0W, *v*=40mm/s, *f*=3.0kHz, *N*=80)



(b) Cross section ($Pd_{77}Cu_6Si_{17}$, *P*=3.0W, *v*=40mm/s, *f*=3.0kHz, *N*=80)



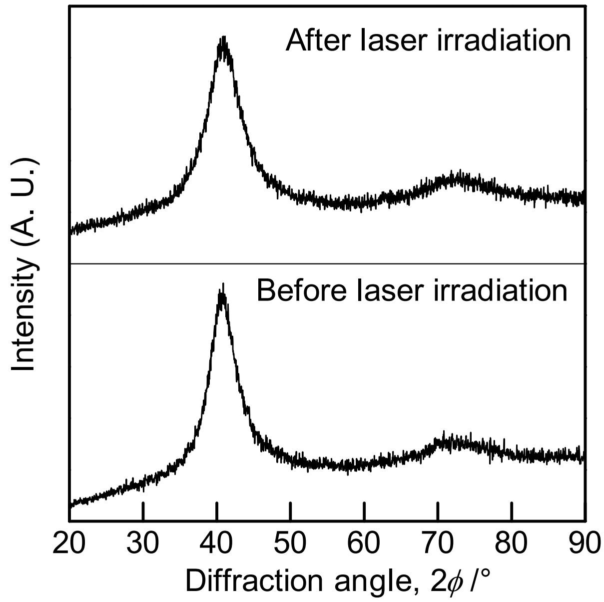
(c) Surface ($Pd_{40}Ni_{40}P_{20}$, *P*=1.5W, *v*=40mm/s, *f*=3.0kHz, *N*=50)



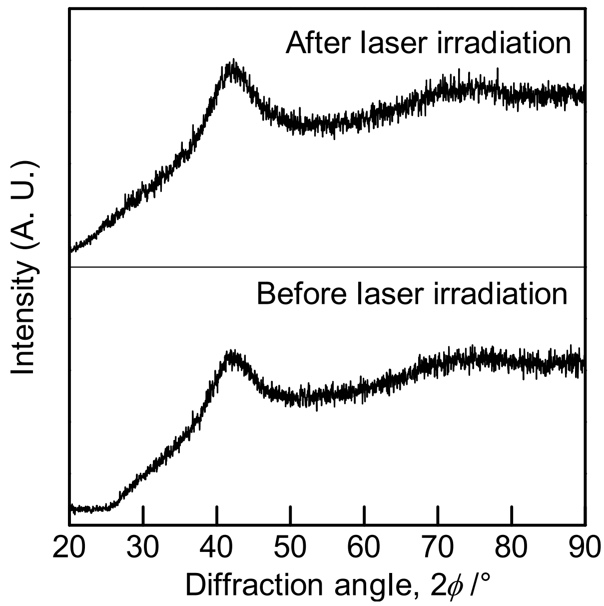
(d) Cross section ($Pd_{40}Ni_{40}P_{20}$, *P*=1.5W, *v*=40mm/s, *f*=3.0kHz, *N*=60)

Fig. 3 SEM images of surface and cross section of formed specimen and/or ablation were not observed at the surfaces of both materials. The thickness at the laser irradiated part was slightly increased. This shows bending by temperature gradient mechanism, which is a characteristic bending mechanism of laser forming, happened.

Figure 4 plots micro-XRD patterns at the bending areas of $Pd_{77}Cu_6Si_{17}$ and $Pd_{40}Ni_{40}P_{20}$, respectively. Broad diffraction patterns which are characteristic of amorphous were obtained for both materials. It is confirmed that both materials became amorphous after laser forming.



(a) $Pd_{77}Cu_6Si_{17}$ (P=3.0W, v=40mm/s, f=3.0kHz, N=80, θ=85º)



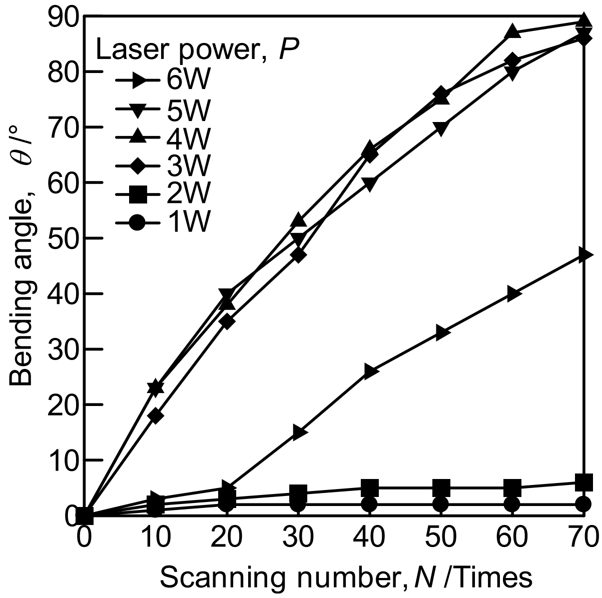
(b) $Pd_{40}Ni_{40}P_{20}$ (P=2.0W, v=40mm/s, f=3.0kHz, N=80, θ=81º)

Fig. 4 Micro-XRD patterns of specimen before and after laser forming

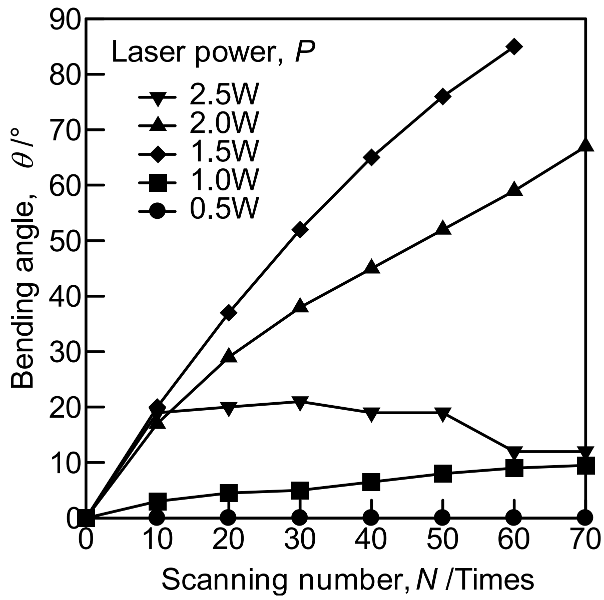
3.2 Scanning Number

Relations between bending angle and scanning number for $Pd_{77}Cu_6Si_{17}$ and $Pd_{40}Ni_{40}P_{20}$ specimens are illustrated in Fig. 5. In both cases, scanning velocity was v=40mm/s and Q-sw frequency was f=3.0kHz.

As scanning number increased, bending angle also increased but increasing rate decreased. The increasing rates of bending angles were different when laser power was changed. In other materials, the same phenomenon is also observed [(1)-(4)]. The reason has not yet resolved although work hardening, thickening due to temperature gradient mechanism, increase of bending stiffness, residual stress caused in the previous laser irradiation, change of microstructure and so on are suggested. It is considerable that since the laser beam was irradiated perpendicular to the specimen, bending angle approached to 90º but it did not exceed the angle.



(a) $Pd_{77}Cu_6Si_{17}$



(b) $Pd_{40}Ni_{40}P_{20}$

Fig. 5 Relation between bending angle and scanning number (v=40mm/s, f=3.0kHz)

3.3 Laser Power

Effect of laser power on bending angle is shown in Fig. 6. Scanning velocity was v=40mm/s, Q-sw frequency was f=3.0kHz and scanning number was N=50. When laser power was larger, that means laser energy was larger, bending angle supposed to become larger, however, bending angle had a peak because thermal stress induced by rapid heating decreased when laser power was too large and a part of surface melted as shown in Fig. 7. Therefore, bending angle became maximum when laser power was from 3 to 5W in $Pd_{77}Cu_6Si_{17}$ case and from 1.5 to 2W in $Pd_{40}Ni_{40}P_{20}$ case.

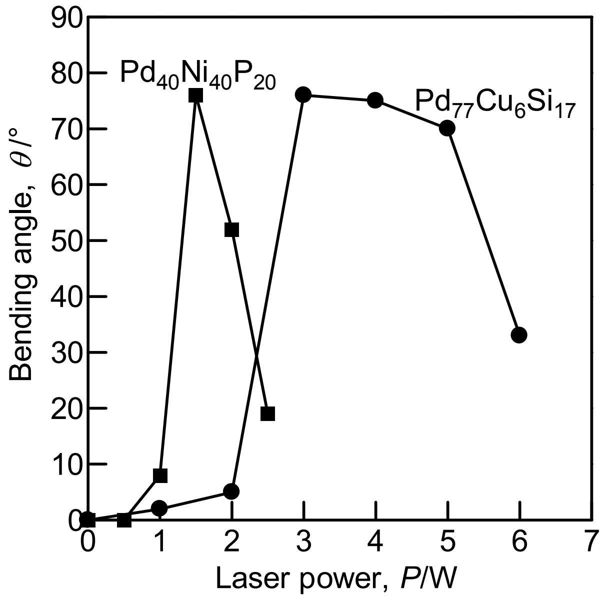


Fig. 6 Relation between bending angle and laser power (v=40mm/s, f=3.0kHz, N=50)

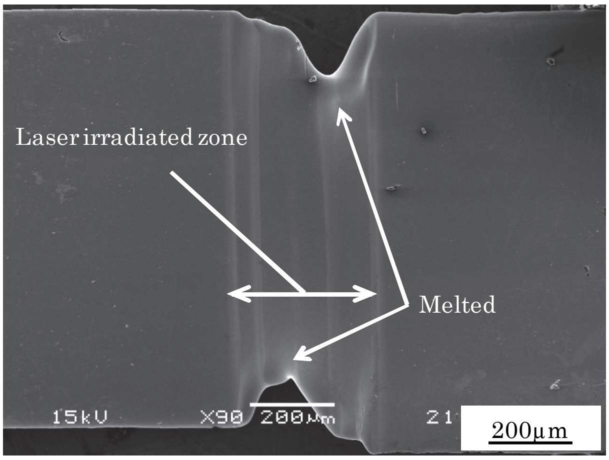


Fig. 7 SEM image at melted surface ($Pd_{40}Ni_{40}P_{20}$, P=2.5W, v=40mm/s, f=3.0kHz, N=50)

3.4 Scanning Velocity

Figure 8 expresses relation between bending angle and scanning velocity at laser power of P=3.0W($Pd_{77}Cu_6Si_{17}$) and 1.5W($Pd_{40}Ni_{40}P_{20}$), Q-sw frequency of f=3.0kHz and scanning number of N=50. Taking laser energy into account, bending angle would be inversely proportional to scanning velocity. But it had a peak because thermal stress reduced by occurring surface melting when scanning velocity was too slow. Therefore, it seems that bending angle becomes maximum at v=30-45mm/s in $Pd_{77}Cu_6Si_{17}$ case and v=30-40mm/s in $Pd_{40}Ni_{40}P_{20}$ case, however, as scanning velocity increased, bending angle decreased rapidly in this range. This reason is assumed that thermal stress became small due to happening crystallization and volume reduction at the laser irradiated region. This phenomenon may be the characteristic for materials like metallic glass showing volume reduction at the elevated temperature, and further investigation is needed.

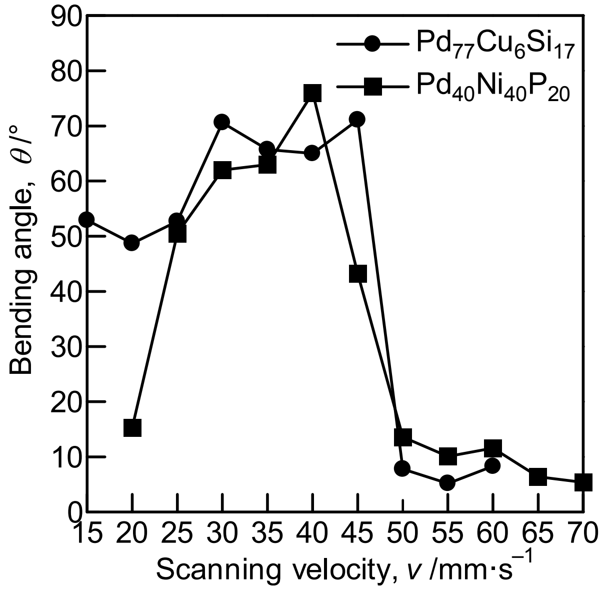


Fig. 8 Relation between bending angle and scanning velocity

(P=3.0W($Pd_{77}Cu_6Si_{17}$), 1.5W($Pd_{40}Ni_{40}P_{20}$), f=3.0kHz, N=50)

3.5 Q-sw Frequency

Figure 9 shows effect of Q-sw frequency on bending angle for $Pd_{77}Cu_6Si_{17}$ and $Pd_{40}Ni_{40}P_{20}$, respectively. Scanning velocity was v=40mm/s and scanning number was N=50. Laser power was P=3.0W for $Pd_{77}Cu_6Si_{17}$ and P=1.5W for $Pd_{40}Ni_{40}P_{20}$. In the case of $Pd_{77}Cu_6Si_{17}$, bending angle was almost constant when frequency was from 2.5 to 5.0kHz and in other ranges, bending did not confirmed or became unstable due to deformation by not temperature gradient mechanism but buckling mechanism.

On the other hand, in the case of $Pd_{40}Ni_{40}P_{20}$, bending angle was larger as frequency was smaller when frequency was from 3 to 12kHz. Except this frequency range, bending was also unstable due to occurring buckling mechanism and bending angle became smaller.

4. Conclusions

Laser forming of thin films of palladium based metallic glasses was carried out and bending of them were succeeded. From the experimental results, followings were obtained.

(1) Thin film of $Pd_{77}Cu_6Si_{17}$ was bent until θ=89.0º and that of $Pd_{40}Ni_{40}P_{20}$ was bent until θ=86.5º.

(2) Both thin films of $Pd_{77}Cu_6Si_{17}$ and $Pd_{40}Ni_{40}P_{20}$ did not crystallize and were amorphous after laser forming.

(3) As scanning number increased, bending angle also increased but increasing rate decreased.

(4) When laser power was changed, bending angle had a peak at P=1.5W in $Pd_{77}Cu_6Si_{17}$ case and at P=3.0W in $Pd_{40}Ni_{40}P_{20}$ case.

(5) When scanning velocity was varied, bending angle had a broad peak and almost constant at v=30-45mm/s in $Pd_{77}Cu_6Si_{17}$ case and v=30-40mm/s in $Pd_{40}Ni_{40}P_{20}$ case.

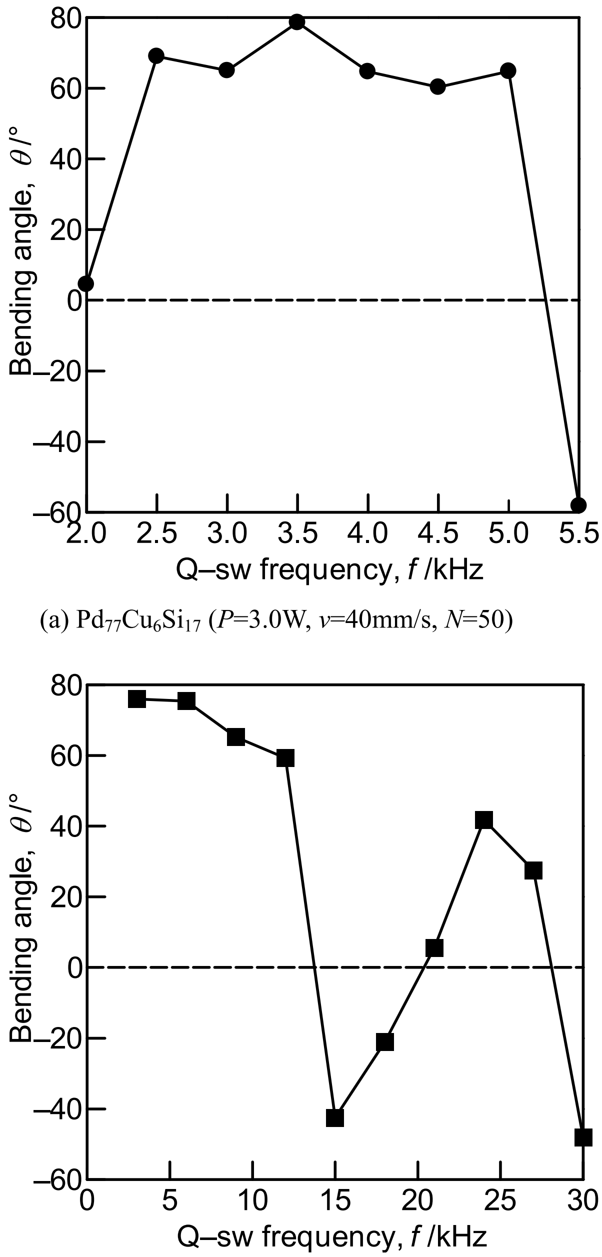
(6) When Q-sw frequency was changed, bending angle had a broad peak at from 2.5 to 5.0kHz

in $Pd_{77}Cu_6Si_{17}$ case, but that was larger as frequency was smaller in $Pd_{40}Ni_{40}P_{20}$ case.

Further works should be required to clarify the mechanism of occurring plastic deformation of metallic glasses in laser forming process. Possibility of applying laser forming process to other metallic glasses and forming into three-dimensional shape, and mechanical properties of laser formed thin films of metallic glasses should be investigate, too.

Acknowledgements

The authors would like to acknowledge Professor Kawamura and Dr. Yamasaki of Kumamoto University for supplying test materials. A part of this work was supported by Grant-in-Aid for Young Scientists (B) 19760513.



(a) $Pd_{77}Cu_6Si_{17}$ (P=3.0W, v=40mm/s, N=50)

(b) $Pd_{40}Ni_{40}P_{20}$ (P=1.5W, v=40mm/s, N=50)

Fig. 9 Relation between bending angle and s Q-sw frequency

References

(1) Majumdar, J. D., Nath, A. K., and Manna, I., Studies on laser bending of stainless steel, *Materials Science and Engineering*, Vol. A 385 (2004), pp. 113-122.

(2) Merklein, M., Hennige, T., and Geiger, M., Laser forming of aluminium and aluminium alloys –microstructural investigation, *Journal of Materials Processing Technology*, Vol. 115 (2001), pp. 159-165.

(3) Geiger, M., Merklein, M., and Pitz, M., Laser and forming technology –an idea and the way of implementation, *Journal of Materials Processing Technology*, Vol. 151 (2004), pp. 3-11.

(4) Chen, D. J., and Wu, S. C., Studies on laser forming of Ti-6Al-4V alloy sheet, *Journal of Materials Processing Technology*, Vol. 152 (2004), pp. 62-65.

(5) Gartner, E., Fruhauf, J., Loschner, U., and Exner, H., Laser bending of etched silicon microstructures, *Microsystem Technologies*, Vol. 7 (2001), pp. 23-26.

(6) Otsu, M., Fukugawa, H., Takashima, K., Laser forming of single crystalline silicon and glass foils, *Journal of Japan Society for Technology of Plasticity*, Vol. 49, No. 570 (2008), pp. 675-679. (in Japanese)

(7) Kawamura, Y., Nakamura, T., and Inoue, A., Superplasticity in $Pd_{40}Ni_{40}P_{20}$ metallic glass, *Scripta Materialia*, Vol. 39, No. 3 (1998), pp. 301-306.

(8) Yamauchi, Y., Hata, S., Sakurai, J., and Shimokohbe, A., Combinatorial search for low resistivity Pd-Cu-Si thin film metallic glass compositions, *Japanese Journal of Applied Physics*, Vol. 45, No. 7 (2006), pp. 5911-5919.